Element-specific determination of the depth dependence of magnetization and magnetic moment across a buried interface using soft x-ray standing waves

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INTRODUCTION

The detailed characterization of buried solid-solid interfaces has become more and more important as the sizes of many scientifically interesting and technologically relevant structures shrink to the nanometer scale. For example, multilayer metal structures at the nanoscale exhibit giant magnetoresistance (GMR) effects and are now routinely used in high-density recording heads, with the properties of the interfaces, e.g. as to how they scatter electrons of different spins, being crucially important for device performance. As another example, gate oxide thicknesses in the field effect transistors which drive current computing logic are also being pushed into the nanometer regime, with the nature of the chemical states and atomic structure near the interfaces involved again emerging as key properties to understand and control for future developments. Other examples for the need to non-destructively study buried interfaces in multilayer or other more complex nanostructures abound. We here present the first results from a newly developed method for non-destructively studying surfaces and buried interfaces [1]. This uses photoemission from wedge-shaped layered samples, as excited by soft x-ray standing waves (XSWs), but in future work the detected emission could also be fluorescent x-rays to permit studying deeper interfaces.

We here consider a particular magnetic/non-magnetic interface between Fe (a ferromagnet that can take on a non-zero net macroscopic magnetization) and Cr (normally an antiferromagnet with zero net magnetization). Such an interface is of high interest because Fe/Cr is a prototypical example of a system exhibiting large GMR effects. Beyond this, however, other ferromagnetic/antiferromagnetic interfaces, if prepared with a proper sequence of annealing and magnetic field exposure, can lead to a “pinning” of one of the ferromagnetic layers in a multilayer structure via the so-called exchange bias (EB) effect. The EB effect is not understood at present, and it also depends on the detailed atomic, electronic, and magnetic properties of the interface.

We here present the first measurements of magnetic order and local spin moments at the buried Fe/Cr interface by utilizing XSW-excited photoemission, in combination with magnetic circular dichroism (MCD). The basic methodology is illustrated in the left portion of Fig. 1, and is discussed further below. From the analysis of such MCD data, the magnetic moments of Cr at the interface are found to be anti-ferromagnetically coupled to the Fe moments, while the magnetization of Fe is also reduced near the interface. Fitting our data to a simple theoretical model permits extracting more quantitative conclusions concerning the depth dependence of magnetization and the spin moment on each atom.

EXPERIMENTAL METHOD

The measurements have been carried at the newly-commissioned elliptically polarized undulator (EPU) beamline 4.0.2 at the ALS, using the advanced photoelectron diffractometer (APSD) that has been relocated recently to it from beamline 9.3.2. The sample configuration is shown in the left panel of Fig. 1. A high-quality soft x-ray multilayer reflector with structure

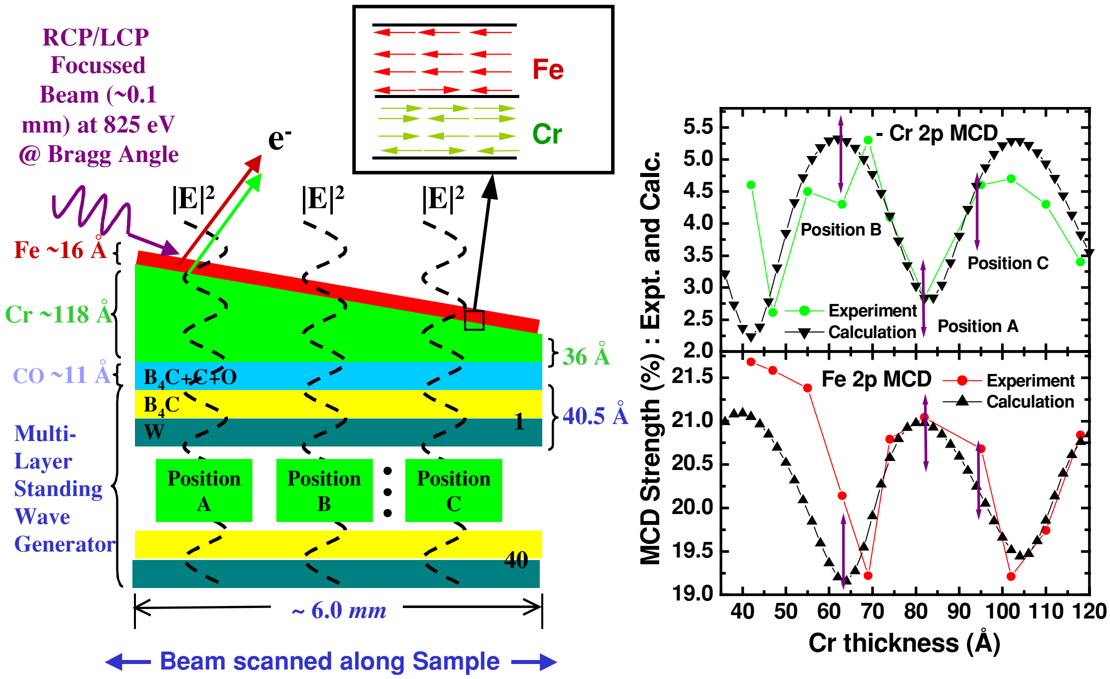

Figure 1. The use of strong soft x-ray standing waves, as produced by a B_4C/W multilayer, in combination with a wedge-shaped Fe-Cr bilayer sample, to study the magnetic properties of both Fe and Cr through the bilayer. The Fe layer is magnetized with its magnetization vector pointing from left to right in the figure. The left image indicates how an x-ray beam incident on the multilayer at its 1st-order Bragg angle produces a very strong standing wave, as judged by the value of $|E^2|$. The small size of the beam (~0.1 mm diam.) also permits scanning it across the sample so as to effectively scan the standing wave through the interface. The right panel shows the variation of both Fe and Cr MCD signals, as measured in 2p photoemission, with the position of the standing wave relative to the interface. Two full cycles have been measured, and three reference positions A, B, and C are shown on both sides of the figure. The calculated curves are based on a specific model of the variation of the magnetizations of Fe and Cr across the interface. The inset at top shows a qualitative picture of the interface, with both elements retaining the same local spin moment, but changing the nature of their magnetic order near the interface.

$(B_4C(20.5\ \text{Å})/W(20.5\ \text{Å}))_{40}$ was prepared outside of vacuum, using a facility in the LBNL Center for X-ray Optics. After transfer of this multilayer into the APSD sample preparation chamber, wedge-shaped bilayers of Fe (constant thickness 16 Å) on Cr (wedge thickness from 118 Å to 36 Å) were grown on its outermost B_4C surface using water-cooled Knudsen cells. All bilayer depositions and photoemission experiments were carried out in the low 10^{-10} torr regime. After deposition, the Fe layer was fully magnetized by placing it in a field of ~500 Gauss oriented parallel to the surface, and thus also to within about 10° of the incidence directions used for the x-rays. Bragg reflection of 825 eV x-rays from this multilayer provided strong standing wave effects with modulations of as high as 50% from maximum to minimum; this standing wave is furthermore very little affected by the presence of the bilayer, being essentially constant in profile across the sample, as indicated in Fig. 1. Scanning the small x-ray spot from the EPU across the sample thus effectively permits scanning the standing wave through the interface. In fact, the MCD data presented in the left panel of Fig. 1 represent two full cycles of the standing wave having passed through the interface.

RESULTS AND DISCUSSION

A variety of measurements have been carried out on such multilayer+bilayer wedge samples:

- Fe 2p and 3p, as well as Cr 2p and 3p, intensities have been measured as a function of incidence angle and position along the sample, with each intensity showing strong variation over both the multilayer “rocking curve” and the length of the sample. Calculations including all x-ray optical effects on photoemission using a newly-written computer program [1,2] agree excellently with experiment, and permit determining the small degrees of compositional intermixing at various interfaces (Fe/Cr; Cr/B_4C, B_4C/W, and W/B_4C).

- With the incidence angle tuned to the Bragg position, corresponding to a maximum modulation of the standing wave through the bilayer (see left panel of Fig. 1 again), MCD measurements were carried out, again for Fe 2p and 3p, as well as Cr 2p and 3p, emission. The right panel of Fig. 1 summarizes the resulting 2p data, with the 3p data looking very similar to it. Note first that the Fe and Cr MCD signals are opposite in sign, indicating that, at least for magnetization parallel to the surface and the incident x-ray direction, the Cr magnetic moments are aligned on average anti-parallel to those of Fe. Note further that the Cr dichroism is much smaller than that of Fe, by a factor of roughly ¼; thus, although Cr is clearly becoming ferromagnetically ordered near the interface, it is still not as much so as Fe, at least along the in-plane direction we are sensitive to. In addtion, the changes in dichroism of the two species are almost exactly out of phase with one another, indicating that, where Fe has its minimum magnetization, Cr tends to have its maximum. Further analyzing these results more quantitatively by assuming gaussian regions over which the Fe magnetization decreases and the Cr magnetization increases finally yields the excellent agreement between experimental and calculated MCD shown in the figure, and permits determining the detailed depth dependence of magnetization for both species.
- Finally, we have measured the Fe 3s and Cr 3s spectra, which are directly sensitive to the local spin moment on each atom, as summed over all directions of moment orientation in the sample. Doing this as a function of position indicates that the average local spin moments on both species are essentially constant through the interface, rather than changing as in suggested in some prior models for this interface.

CONCLUSIONS

We have thus demonstrated a new type of non-destructive method for carrying out photoemission, as well as and other types of soft-x-ray-excited spectroscopies, with enhanced depth resolution for buried interfaces. This standing wave-plus-wedge approach should be applicable to a variety of problems. For the Fe/Cr interface, both a reduction of the Fe magnetization and an increase of the anti-parallel Cr magnetization near the interface are observed, with quantitative estimates of depth profiles possible. However, the individual spin moments on the two atoms are not found to change with depth. These observations are at least qualitatively consistent with other studies on the same system [2], but go beyond prior work in permitting this for a single sample and buried interface, and in being more quantitative.

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